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Citation: Hackney, Philip and Oppon, Charles (2020) Fatigue Analysis of Additive Manufactured Long Fibre Reinforced Nylon Materials. Procedia CIRP, 51. pp. 678-683. ISSN 2212-8271

Published by: Elsevier

URL: <https://doi.org/10.1016/j.promfg.2020.10.095>
<<https://doi.org/10.1016/j.promfg.2020.10.095>>

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30th International Conference on Flexible Automation and Intelligent Manufacturing (FAIM2021) 15-18 June 2021, Athens, Greece.

Fatigue Analysis of Additive Manufactured Long Fibre Reinforced Nylon Materials

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Abstract

Composite materials due to their high strength to density characteristics are widely used in aerospace, automotive, marine applications etc. Recent developments in Additive Manufacturing processes and materials have enabled the manufacture of end-use functional components. This paper investigates the fatigue behaviour of composite parts processed Additive Manufacturing (AM) process Continuous Fibre Fabrication reinforcement (CFF) method. There are existing data for static material properties however they are only a few published papers on the fatigue performance of parts processed by CFF additive manufacturing. This study investigates by physical and digital simulation, the fatigue life of 0, 2, 4, 6, 8 layer carbon fibre reinforced Nylon ASTM606M test samples. This research has determined design for fatigue guidelines for additively manufactured composite materials, for both for the low and high cycle applications.

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Peer-review under responsibility of the scientific committee of the FAIM 2021.

Keywords; Fused Filament Fabrication; Long Fibre Additive Manufacturing; Tensile Fatigue

1. Introduction

Composite materials are widely used in many applications where a high ratio of strength to weight is critical, traditional composite methods of fabrication have geometric limitations due the manufacturing process, fibre and matrix resin bonding and compaction. The application of Additive layer-based composite manufacture pioneered and commercialized by MarkForged™ with their Carbon Continuous Filament Fabrication (CFF), has enabled the design for manufacture rules to be changed, new geometric and lightweight components are now possible with internal honeycomb load-dependent structures, further reducing weight, improving efficiency and reducing emissions, particularly for aerospace applications. The process interaction and the resultant mechanical static and dynamic materials properties are easily determined from test data, and hence stress simulations allow topology optimized design to further generatively develop highly functional shapes. The 2D layer-based process has limitation to 2D stress, strain load path solutions, for example, a simple 3 point bending of a beam and life cycle material data is limited. This study aims to further develop an understanding of the fatigue behaviour of CFF Additively manufactured test pieces, generate graphical data in the form of stress vs Cycles curves to enable design engineers to innovatively generation the next generation of lightweight products.

2. Experimental Procedure

2.1. Fatigue failure Theory

Fatigue fracture occurs as a three-stage process;

- Initially, a crack is nucleated, usually at the surface of the component. Subsequently,
- Crack propagates over time until a critical crack length is reached.
- Finally, the crack becomes large enough that the material cannot support the nominal applied stress and the material undergoes fast fracture.

Components which breaks, cracks or fails after repetitive usage, can be considered as fatigue failure. Examples of fatigue failure were the airline crashes of the De Havilland Comets in 1954. Three of these passenger jets broke up mid-air and crashed within a single year. Sharp corners around the plane's window openings were found to have acted as stress

concentrators, which initiated cracks. The pressurisation of the aircraft during each flight created stress cycles in the fuselage that propagated the cracks over time. At some point, a critical crack length was reached and fast fracture of the fuselage shell then occurred.

The crack growth rate is a function of the stress level as defined by the Paris equation 1, with initial crack size and material properties. The relationship is expressed in terms of the stress intensity factor K:

$$\frac{da}{dN} = A(\Delta K)^m \dots \dots \dots \text{eq 1}$$

Where a is crack length, A and m are material constants, ΔK dependent on the environment. The stress intensity factor range and β is the geometry factor.

$$\Delta K = \beta \Delta \sigma_{max} \sqrt{\pi a} \dots \dots \text{eq 2}$$

The number of cycles to failure N_f or fatigue life defined by eq3

$$N_f = \int_{a_o}^{a_c} \frac{da}{A(\beta \Delta \sigma \sqrt{\pi a})^m} \dots \dots \dots \text{eq 3}$$

This expression is only valid in the crack propagation stage and does not include crack initiation or rapid fracture and therefore the fatigue life calculated should be taken as an estimate of fatigue life. This expression is more accurate when the crack initiation stage is small (under high stresses).

This expression also assumes that is $stress \sigma_{max}$ is a constant which is not true in many applications [1].

In terms of cyclic life, the division between low cycle and high cycle failure is usually considered to be somewhere between about 10,000 and 50,000 cycles, dependent upon the relative magnitudes of plastic and elastic strains. In any fatigue analysis for a component, whether this be for the Low Cycle Fatigue or High Cycle Fatigue region, it will be necessary to take into account many of the influencing factors which affect fatigue behavior, amongst the major ones of which are:

- Type and nature of loading;
- Size of component and stress or strain distribution;
- Surface finish and directional properties;
- Stress or strain concentrations;
- Mean stress or strain;
- Environmental effects;
- Material properties;
- Strain rate and frequency effects [2].

The fatigue performance of rapid manufactured composite parts has received little research to date. Most numerous references are found for laser sintered metal specimens [3,4]

However, very few references have been found dealing with the fatigue behaviour of AM composite structures. The research of, Afrose et al. (2016) considered the AM PLA FFF manufacturing orientation as a factor of study, and found that specimens built at 45 degrees presented the highest fatigue life expected for every stress level tested. The detected lack of references about the influence of other parameters on fatigue life, as well as a comprehensive study into fatigue behaviour of additive, manufactured FFF PLA parts paper [5].

Research by Hedley, L demonstrated how AM FFF technique could be used for manual fibre reinforcement, whereby channels were manufactured and fibre then threaded through these channels and bonded using a two-part resin to the AM part [6]. This work is an attempt to replicate the automated CFF of the Markforged™ process, used in this research work.

2.2. Sample manufacture

This research followed the methodology, comprising research into Composites, AM of composites and fatigue testing, followed by sample modelling, production and post-processing. The test stage of coupons was physically evaluated by tensile testing and digitally simulated using Ansys Finite Element Analysis, the results were then compared to published and manufactured data. A fatigue test specimen was modelled in CAD which complied with the ASTM E606M Test Standard used for Fatigue Testing using an Instron ElectroPuls® tensile fatigue apparatus. The dimensions of the specimen as shown in figure 1 which is 5 mm thick.

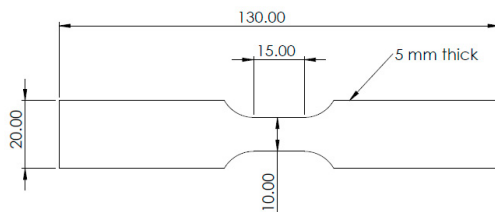


Fig. 1. ASTM E606M Standard Test Sample

The CAD model is exported as STL, and sliced in Eiger MarkForged™ software, to add reinforcement, and build parameters. Fill density was set at 37% to reduce print time and a hexagonal fill was selected to reduce material compared to a solid fill.

In Composite Filament Fabrication (CFF) printing process the specimen must always have at least one layer of Nylon on the bottom and the top of the CFRP layers. So the carbon layer can be deposited more easily and do not disintegrate on the printing bed when the sample is removed. The Nylon layers on the top of the sample are added for symmetry reasons.

Roof and floor layers are set at three concentric rings were chosen, as this was the maximum that could fit in the dimensions of the part.

A total of 40 layers, and roof and floor reinforcement layers set at four shown in figure 2. The maximum amount of reinforcement available for this part is 36 layers. For example 6 layer part, 3 layers are distributed symmetrically vertically through the part with a print time of 2 hours each.

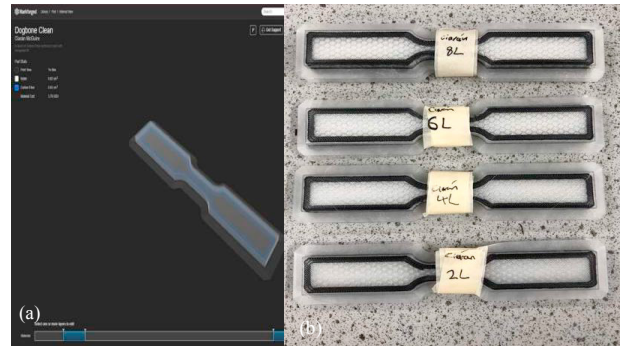


Fig. 2. (a) Eiger slicer software build (b) samples produced

2.3. Experimental testing

The specimens were physically tested and digitally simulated using FEA technique in both tensile and bending under single and cyclic load cases.

The single tests provided the UTS and hence the point to determine the 80%, 60%, 50%, 40% fatigue loading tests.

2.3.1. Tensile test

The samples in Figure 1 and 2, were tested to failure, crosshead speed: 3mm/min, Temperature: 23 °C, Humidity: 50%. The results of 2 – 8 layered un-cycled and 8 layers fatigued are shown in Figure 3.

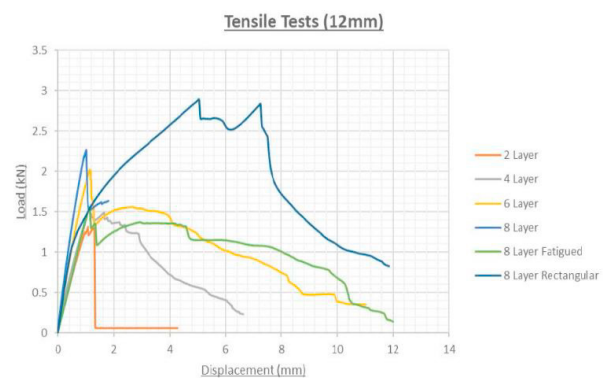


Fig. 3. Tensile tests - Force vs Displacement

The samples failure was characterised by the fibre failure and then fibre pullout from the nylon matrix. The 8 layers fatigued sample which had reached its cyclic limit, demonstrated lower failure stress, proving that even at lower stress levels fatigue affects the properties of the material, summarized in table 1

Table 1. Tensile test results

No. CF Layers/info	0 Layers	2 Layers	4 Layers	6 Layers	8 Layers	8 fatigued
Break displacement (mm)	36.750	1.085	1.155	1.150	1.010	10.300
Max Load (kN)	0.738	1.319	1.542	2.026	2.268	1.550
Max Stress (MPa)	17.290	26.390	30.840	50.640	45.350	36.290
Max Strain (mm/mm)	0.638	0.285	0.443	0.138	1.002	0.265

The samples did not fail at the smallest CSA as expected but at the change in direction of the fibre as shown in figure 5, which was evidenced by the Finite Element Analysis (FEA), coupled with the fibre deposition start point located in these regions also.



Fig. 4. Fatigue testing and failed samples

2.3.2. Fatigue testing

The fatigue stress vs Cycles to failure is shown in figure 5, the first plot on the y-axis at 1 cycle is the 100% max load (i.e.

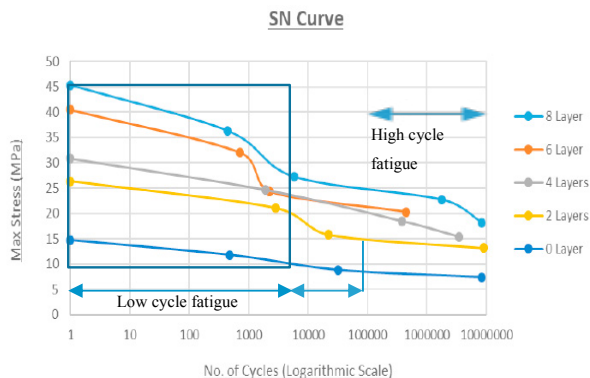


Fig. 5. Stress vs No of cycles (SN) Curves

the value achieved by tensile testing). Fatigue tests were run at different stress levels notably 80%, 60%, 50% until specimen failure or run out (completion of 8m+ cycles).

Each point on the line denotes a percentage of max stress amplitude applied for the test. The 8 layer curve has an extra point on the graph as an additional 40% fatigue test was completed, however, due to this result, no other 40% fatigue

tests were undertaken as it would not result fatigue failure. The graphs follow the traditional Wohler line [7].

As can be seen, the 8, 6, and 2 layers follow a slight sigmoidal curve which appears to be a trend for these materials. However, for the 4 layer specimens, a steady negative correlation can be identified. This could be due to the composition of the specimen and the number and position of data points to create the graph. The results in table 2 demonstrates that the 8 CF layer specimen, which had previously been fatigue tested, reached a max load of 1.550 kN after being tensile tested. This is a decrease of 718 N of the max load of a previously untested specimen. This demonstrated that some degree of weakening of the specimen had occurred due to crack propagation.

Table 2. Fatigue Stress Vs Cycles to failure

Fatigue (80%)					
No. carbon fibre layers	8	6	4	2	0
Max Load (kN)	1.814	1.600	1.233	1.055	0.591
Max Stress (MPa)	36.288	32.000	24.660	21.100	11.810
No. cycles	443	720	1,905	2,827	480
Break	Yes	Yes	Yes	Yes	Yes

Fatigue (60%)					
No. carbon fibre layers	8	6	4	2	0
Max Load (kN)	1.361	1.216	0.925	0.791	0.443
Max Stress (MPa)	27.216	24.312	18.504	15.828	8.8572
No. cycles	5,838	2,257	380,627	22,076	31,750
Break	Yes	Yes	Yes	Yes	Yes

Fatigue (50%)					
No. carbon fibre layers	8	6	4	2	0
Max Load (kN)	1.134	1.013	0.771	0.6595	0.369
Max Stress (MPa)	22.68	20.26	15.42	13.19	7.381
No. cycles	1,797,563	441,106	3,433,574	8,971,959	8,591,453
Break	Yes	Yes	Yes	No	No

Fatigue (40%)	
No. carbon fibre layers	8
Max Load (kN)	0.907
Max Stress (MPa)	18.144
No. cycles	8380070
Break	No

2.3.3. Three-Point Bend Test

Three-point bending evaluation of the specimens. The specimens used for fatigue testing were recycled for these tests. The span of the piece tested for 3 point bends was 40 mm, with a cross-sectional area of 50 mm². The diameter of the centre tool was 10 mm

It can be seen that after the carbon fibres have broken, the specimen takes on a plastic region of deformation, which is to be expected, with only the nylon matrix material is remaining intact.

Table 3. Three-point bend results

N o	Line colour	CF Layer s	Max Load kN	Max Stress MPa	Max Strain mm	Max Displacement mm	Modulus MPa
1	Blue	8	0.4265	8.530	0.133	5.329	90.93
2	Red	6	0.3925	7.850	0.128	5.013	82.30
3	Purple	4	0.3746	7.492	0.123	4.930	77.35
4	Black	2	0.3115	6.230	0.069	2.739	74.77
5	Khaki	0	0.1666	3.332	0.218	8.698	16.47
6	Green	rectangular	0.3211	6.422	0.113	4.532	49.50

2.4. Finite Element simulation

In addition to the evaluation of existing literature and the physical experimental tests, computer simulations were developed using ANSYS 19.0 workbench to achieve a finite element analysis. The simulation process, the objective of evaluation of fibre orientations and distributions can be achieved

The analysis comprised the designing the dog bone shaped specimen with the internal carbon fibre layer reinforcement. To do this, feature sweeps and then swept cuts were made to the dimensions of a single carbon fibre strand. These entities were then offset and mirrored to create symmetrical parts, imported into ANSYS and material and bonding parameters set for material and matrix shown in figure 6.

The model then meshed and fixed support applied at one end and the force applied at the opposite end, defined from the tensile test UTS results from Table 1. The resultant model had 105,000 nodes and 51,000 elements.

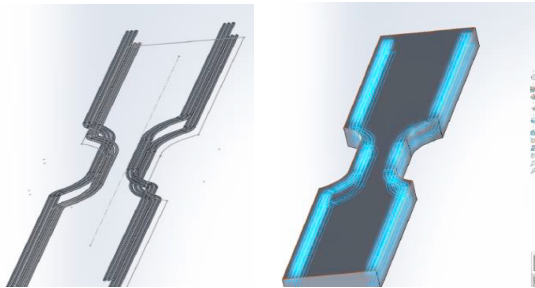


Fig. 6. CAD model of fibre and composite

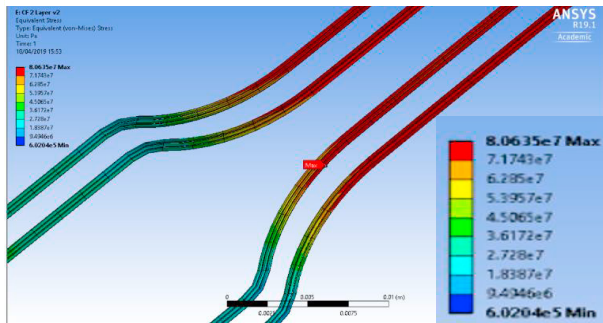


Fig. 7. – FEA stress analysis of CFF two Layer (Matrix material Hidden)

The static tensile stress FEA results show the maximum stress occurs where the fibre changes direction but held at an angle by the matrix, hence providing bending stress on the fibre rather than a plane tensile stress if the fibre was free to rotate. As the Carbon fibres are brittle in this loading direction, this validated the observations from the physical testing stages. Figure 7 shows the maximum stress at the change in direction of the fibre.

3. Discussion, conclusions and further work

3.1. Discussion of results

The main outcome is the more carbon fibre reinforcement a specimen contains, the higher the max stress the specimen can

stress the greater the number of cycles, the less reinforcement the specimen contained.

High-quality images from the Alicona Optical Microscope allow further analysis of the local anisotropic material behaviour. The carbon fibre reinforcement can be recognised as the darker coloured circular pattern closer to the edge of the specimen in Figure 8. Additionally, Figure 8 shows an image viewed at 1000 μm and the nylon fill can be distinguished in its 45° alignment.

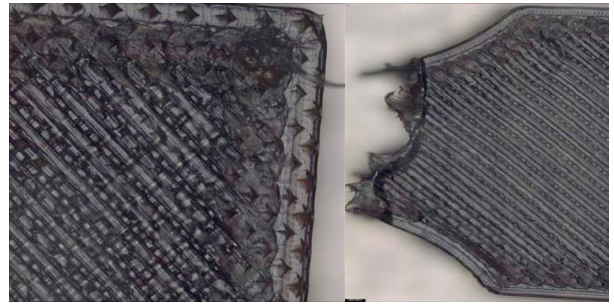


Figure 8 - Optical microscope pictures of carbon reinforcement and failed section

What begins as a fibre fracture can induce a matrix crack, which can induce fibre-matrix de-bonding, which results in fibre pull-out.

Limitation of testing at low stresses, for example, a 2 layer CF specimen at 50% load, it ran for 8,971,959 cycles before the test was stopped. At 5 Hz which means 5 cycles a second $5 \times 60 \times 60 = 18,000$ cycles an hour. $8,971,959 / 18,000 = 498.44$ hours of testing, which is almost 21 days of the machine running continuously.

Single carbon fibre strands were tested and compared to MarkForged™ published Data of 700 MPa a single 0.5 mm fibre failure force of 61.85 N, was comparable to actual testing of 60.65 N, If this value is multiplied by 3 for the 3 concentric rings used in all samples and then further multiplied by 8 it provides an estimate of the tensile strength for the CF reinforced part of an 8 layer specimen. $60.56 \times 3 \times 8 = 1453.44$ N. If the max load of a pure nylon piece tensile tested is added to this, we achieve $1453.44 + 738.1 = 2191.52$ N. This is extremely close to the actual max load value for the additively manufactured part of 2268 N which validates the preceding results. The difference is 76.46 N, (3%) which can be due to the composition of the part and the way the hexagonal nylon structure bonds with the carbon fibre layers. In addition to this, the change in the profile of the carbon fibre as it curves in the specimen is a major factor.

Another contributing factor is the layer discontinuities as the MarkOne™ occasionally struggles with producing all 3 concentric rings with the carbon fibre filament. It can be seen in Figure 10 that the 3D prints did not manufacture as expected, the 3rd ring is incomplete on both samples and there is a gap where the 1st ring appears to commence printing. It also needs to be taken into consideration the minimum cut off the length for carbon fibre filament in the Mark One is 300 mm, this means that at any one point 300 mm is the shortest length of fibre that is currently being printed in the machine.

The reinforcement had little effect on the stiffness and hence Young's modulus of the composite, however, the number of fibre reinforcement has an impact as shown in figure 9 generated from table 4

The calculated strength of the composite determined from the individual fibre strength multiplied by the number of fibres had a close collation within 3%.

4. Conclusions

This paper has determined the fatigue life of long fibre reinforced composite subjected to loads aligned to the fibre orientation and compared to Finite element simulations. The developed stress vs the number of cycles graph has been produced which will allow design engineers to predict life endurance limits for CFF manufactured components under these load conditions.

5. Future work

Future work is required to further develop an understanding of;

- The effect of build orientation to load condition for fatigue applications
- The effect of processing parameters such as extrusion temperature, deposition rate and build chamber, upon fibre pull out from the matrix structure
- The effect of build styles of the fibre reinforcement and matrix infill density on fatigue life

Acknowledgements

The authors would like to acknowledge the contribution and support of Ciaran McGuire who helped undertake the manufacture and testing of samples.

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